

# ***CPT* INVARIANCE TESTS IN NEUTRAL KAON DECAY**

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*CPT* theorem is based on three assumptions: quantum field theory, locality, and Lorentz invariance, and thus it is a fundamental probe of our basic understanding of particle physics. Strangeness oscillation in  $K^0 - \bar{K}^0$  system, described by the equation

$$i \frac{d}{dt} \begin{bmatrix} K^0 \\ \bar{K}^0 \end{bmatrix} = [M - i\Gamma/2] \begin{bmatrix} K^0 \\ \bar{K}^0 \end{bmatrix},$$

where  $M$  and  $\Gamma$  are hermitian matrices (see PDG review [1], references [2,3], and KLOE paper [5] for notations and previous literature), allows a very accurate test of *CPT* symmetry; indeed since *CPT* requires  $M_{11} = M_{22}$  and  $\Gamma_{11} = \Gamma_{22}$ , the mass and width eigenstates,  $K_{S,L}$ , have a *CPT*-violating piece,  $\delta$ , in addition to the usual *CPT*-conserving parameter  $\epsilon$ :

$$\begin{aligned} K_{S,L} &= \frac{1}{\sqrt{2(1+|\epsilon_{S,L}|^2)}} \left[ (1 + \epsilon_{S,L}) K^0 \pm (1 - \epsilon_{S,L}) \bar{K}^0 \right] \\ \epsilon_{S,L} &= \frac{-i\Im(M_{12}) - \frac{1}{2}\Im(\Gamma_{12}) \mp \frac{1}{2} \left[ M_{11} - M_{22} - \frac{i}{2}(\Gamma_{11} - \Gamma_{22}) \right]}{m_L - m_S + i(\Gamma_S - \Gamma_L)/2} \\ &\equiv \epsilon \pm \delta. \end{aligned} \tag{1}$$

Using the phase convention  $\Im(\Gamma_{12}) = 0$ , we determine the phase of  $\epsilon$  to be  $\varphi_{SW} \equiv \arctan \frac{2(m_L - m_S)}{\Gamma_S - \Gamma_L}$ . Imposing unitarity to an arbitrary combination of  $K^0$  and  $\bar{K}^0$  wave functions, we obtain the Bell-Steinberger relation [4] connecting *CP* and *CPT* violation in the mass matrix to *CP* and *CPT* violation in the decay; in fact, neglecting  $\mathcal{O}(\epsilon)$  corrections to the coefficient of the *CPT*-violating parameter,  $\delta$ , we can write [5]

$$\begin{aligned} \left[ \frac{\Gamma_S + \Gamma_L}{\Gamma_S - \Gamma_L} + i \tan \phi_{SW} \right] \left[ \frac{\Re(\epsilon)}{1 + |\epsilon|^2} - i\Im(\delta) \right] = \\ \frac{1}{\Gamma_S - \Gamma_L} \sum_f A_L(f) A_S^*(f), \end{aligned} \tag{2}$$

where  $A_{L,S}(f) \equiv A(K_{L,S} \rightarrow f)$ . We stress that this relation is phase-convention-independent. The advantage of the neutral kaon system is that only a few decay modes give significant contributions to the r.h.s. in Eq. (2); in fact, defining for the hadronic modes

$$\alpha_i \equiv \frac{1}{\Gamma_S} \langle \mathcal{A}_L(i) \mathcal{A}_S^*(i) \rangle = \eta_i \mathcal{B}(K_S \rightarrow i),$$

$$i = \pi^0 \pi^0, \pi^+ \pi^-(\gamma), 3\pi^0, \pi^0 \pi^+ \pi^-(\gamma), \quad (3)$$

the recent data from CPLEAR, KLOE, KTeV, and NA48 have led to the following determinations (the analysis described in Ref. 5 has been updated by using the recent measurements of  $K_L$  branching ratios from KTeV [6,7], NA48 [8,9], and the results described in the  $CP$  violation in  $K_L$  decays minireview, and the recent KLOE result [10])

$$\alpha_{\pi^+ \pi^-} = ((1.112 \pm 0.010) + i(1.061 \pm 0.010)) \times 10^{-3},$$

$$\alpha_{\pi^0 \pi^0} = ((0.493 \pm 0.005) + i(0.471 \pm 0.005)) \times 10^{-3},$$

$$\alpha_{\pi^+ \pi^- \pi^0} = ((0 \pm 2) + i(0 \pm 2)) \times 10^{-6},$$

$$|\alpha_{\pi^0 \pi^0 \pi^0}| < 1.5 \times 10^{-6} \quad \text{at } 95\% \text{ CL}. \quad (4)$$

The semileptonic contribution to the right-handed side of Eq. (2) requires the determination of several observables: we define [2,3]

$$\mathcal{A}(K^0 \rightarrow \pi^- l^+ \nu) = \mathcal{A}_0(1 - y),$$

$$\mathcal{A}(K^0 \rightarrow \pi^+ l^- \nu) = \mathcal{A}_0^*(1 + y^*)(x_+ - x_-)^*,$$

$$\mathcal{A}(\overline{K}^0 \rightarrow \pi^+ l^- \nu) = \mathcal{A}_0^*(1 + y^*),$$

$$\mathcal{A}(\overline{K}^0 \rightarrow \pi^- l^+ \nu) = \mathcal{A}_0(1 - y)(x_+ + x_-), \quad (5)$$

where  $x_+$  ( $x_-$ ) describes the violation of the  $\Delta S = \Delta Q$  rule in  $CPT$ -conserving (violating) decay amplitudes, and  $y$  parametrizes  $CPT$  violation for  $\Delta S = \Delta Q$  transitions. Taking advantage of their tagged  $K^0(\overline{K}^0)$  beams, CPLEAR has measured  $\Im(x_+)$ ,  $\Re(x_-)$ ,  $\Im(\delta)$ , and  $\Re(\delta)$  [11]. These determinations have been improved in Ref. 5 by including the

information  $A_S - A_L = 4[\Re(\delta) + \Re(x_-)]$ , where  $A_{L,S}$  are the  $K_L$  and  $K_S$  semileptonic charge asymmetries, respectively, from the PDG [12] and KLOE [13]. Here we are also including the  $T$ -violating asymmetry measurement from CPLEAR [14].

**Table 1:** Values, errors, and correlation coefficients for  $\Re(\delta)$ ,  $\Im(\delta)$ ,  $\Re(x_-)$ ,  $\Im(x_+)$ , and  $A_S + A_L$  obtained from a combined fit, including KLOE [5] and CPLEAR [14].

	value	Correlations coefficients				
$\Re(\delta)$	$(3.0 \pm 2.3) \times 10^{-4}$	1				
$\Im(\delta)$	$(-0.66 \pm 0.65) \times 10^{-2}$	-0.21	1			
$\Re(x_-)$	$(-0.30 \pm 0.21) \times 10^{-2}$	-0.21	-0.60	1		
$\Im(x_+)$	$(0.02 \pm 0.22) \times 10^{-2}$	-0.38	-0.14	0.47	1	
$A_S + A_L$	$(-0.40 \pm 0.83) \times 10^{-2}$	-0.10	-0.63	0.99	0.43	1

The value  $A_S + A_L$  in Table 1 can be directly included in the semileptonic contributions to the Bell Steinberger relations in Eq. (2)

$$\begin{aligned}
& \sum_{\pi\ell\nu} \langle \mathcal{A}_L(\pi\ell\nu) \mathcal{A}_S^*(\pi\ell\nu) \rangle \\
&= 2\Gamma(K_L \rightarrow \pi\ell\nu) (\Re(\epsilon) - \Re(y) - i(\Im(x_+) + \Im(\delta))) \\
&= 2\Gamma(K_L \rightarrow \pi\ell\nu) ((A_S + A_L)/4 - i(\Im(x_+) + \Im(\delta))) . \quad (6)
\end{aligned}$$

Defining

$$\alpha_{\pi\ell\nu} \equiv \frac{1}{\Gamma_S} \sum_{\pi\ell\nu} \langle \mathcal{A}_L(\pi\ell\nu) \mathcal{A}_S^*(\pi\ell\nu) \rangle + 2i \frac{\tau_{K_S}}{\tau_{K_L}} \mathcal{B}(K_L \rightarrow \pi\ell\nu) \Im(\delta) , \quad (7)$$

we find:

$$\alpha_{\pi\ell\nu} = ((-0.2 \pm 0.5) + i(0.1 \pm 0.5)) \times 10^{-5} .$$

Inserting the values of the  $\alpha$  parameters into Eq. (2), we find

$$\begin{aligned}
\Re(\epsilon) &= (161.1 \pm 0.5) \times 10^{-5}, \\
\Im(\delta) &= (-0.7 \pm 1.4) \times 10^{-5}. \quad (8)
\end{aligned}$$

The complete information on Eq. (8) is given in Table 2.

**Table 2:** Summary of results: values, errors, and correlation coefficients for  $\Re(\epsilon)$ ,  $\Im(\delta)$ ,  $\Re(\delta)$ , and  $\Re(x_-)$ .

	value	Correlations coefficients			
$\Re(\epsilon)$	$(161.1 \pm 0.5) \times 10^{-5}$	+ 1			
$\Im(\delta)$	$(-0.7 \pm 1.4) \times 10^{-5}$	+ 0.09	1		
$\Re(\delta)$	$(2.4 \pm 2.3) \times 10^{-4}$	+ 0.08	-0.12	1	
$\Re(x_-)$	$(-4.1 \pm 1.7) \times 10^{-3}$	+ 0.14	0.22	-0.43	1

Now the agreement with  $CPT$  conservation,  $\Im(\delta) = \Re(\delta) = \Re(x_-) = 0$ , is at 18% C.L.

The allowed region in the  $\Re(\epsilon) - \Im(\delta)$  plane at 68% CL and 95% C.L. is shown in the top panel of Fig. 1.

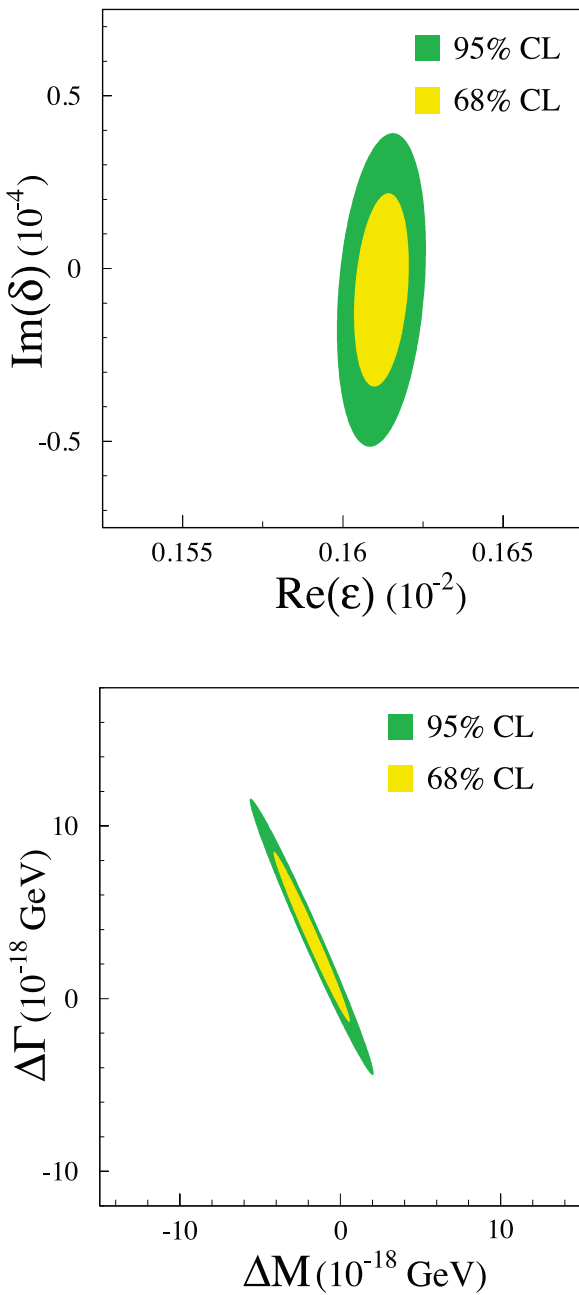
The process giving the largest contribution to the size of the allowed region is  $K_L \rightarrow \pi^+ \pi^-$ , through the uncertainty on  $\phi_{+-}$ .

The limits on  $\Im(\delta)$  and  $\Re(\delta)$  can be used to constrain the  $K^0 - \bar{K}^0$  mass and width difference

$$\delta = \frac{i(m_{K^0} - m_{\bar{K}^0}) + \frac{1}{2}(\Gamma_{K^0} - \Gamma_{\bar{K}^0})}{\Gamma_S - \Gamma_L} \cos \phi_{SW} e^{i\phi_{SW}} [1 + \mathcal{O}(\epsilon)].$$

The allowed region in the  $\Delta M = (m_{K^0} - m_{\bar{K}^0})$ ,  $\Delta\Gamma = (\Gamma_{K^0} - \Gamma_{\bar{K}^0})$  plane is shown in the bottom panel of Fig. 1. As a result, we improve on the previous limits (see for instance, P. Bloch in Ref. 12) and in the limit  $\Gamma_{K^0} - \Gamma_{\bar{K}^0} = 0$  we obtain

$$-4.0 \times 10^{-19} \text{ GeV} < m_{K^0} - m_{\bar{K}^0} < 4.0 \times 10^{-19} \text{ GeV} \quad \text{at } 95 \% \text{ C.L.}$$



**Figure 1:** Top: allowed region at 68% and 95% C.L. in the  $\Re(\epsilon)$ ,  $\Im(\delta)$  plane. Bottom: allowed region at 68% and 95% C.L. in the  $\Delta M$ ,  $\Delta \Gamma$  plane.

## References

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